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# Green Building Performance Prediction/Assessment

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## Abstract

To make decisions, building designers need to predict and assess the performance of their ideas with respect to various criteria, such as comfort, esthetics, energy, environmental impact, economics, etc. Performance prediction with respect to environmental impact requires complicated models and massive computations, which are usually possible only through computer-based tools. This paper focuses on the use of computer-based tools for predicting and assessing building performance with respect to environmental impact criteria for the design of green buildings. It contains analyses of green performance prediction/assessment and descriptions of available tools, along with discussions on their use by different types of users. Finally, it includes analyses of the cost and benefits of green performance prediction and assessment.

## Introduction

The design of buildings requires collaboration of all building disciplines and interested parties from the initial, schematic phases of building design (Larsson, 1993, 1995). To assure green performance, this collaboration must continue throughout the building lifecycle, from construction, commissioning and operation, to remodeling, retrofitting and eventually demolishing the building. The objective of these collaborative efforts is to make the "right" decisions, especially during the building design phases, when decisions have a long-lasting effect on the performance of the resulting building.

To make informed decisions, building designers need to *predict* and *assess* the performance of their ideas with respect to various criteria, related to comfort, esthetics, energy, environmental impact, economics, etc. The design process is an iteration of generating ideas, predicting their performance and then assessing it, to determine what the next step should be (Figure 1) [Papamichael and Protzen, 1993; Papamichael, 1999]. Inaccurate performance prediction may lead to buildings that behave worse than expected. Inaccurate assessment may lead to buildings that behave as expected but are poor performers. The opposite, of course, may also be true, that is through inaccurate performance prediction and assessment end up with a building that performs better than expected, being a good performer as well. The bottom line is that performance prediction and assessment provide the basis for informed decisions, increasing the chances for better buildings and minimizing the risk for failures.

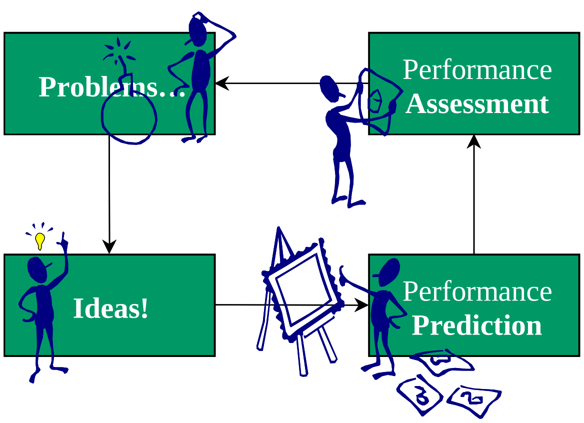


**Figure 1**. The design process as an iteration of predicting and assessing the performance of ideas to resolving problems.

## Performance Prediction

Performance *prediction* involves the development of models that behave similarly to the way that the actual building would if it were built. Such models range from images in our brains, to sketches, drawings, scale models, hand calculations and computer-based simulations.

Architects and engineers use various methods to predict and assess performance, depending on the type of performance considered and the level of accuracy desired.

Initially through sketches and later through increasingly detailed drawings, *architects* predict and assess performance with respect to various qualitative criteria, such as spatial arrangement, esthetic appeal, etc. Occasionally, they build physical scale models to better predict, understand and demonstrate performance. In addition to drawings and scale models, *engineers* use various types of computations to predict performance with respect to quantitative criteria, such structural and energy requirements, comfort, environmental impact, etc.

### *Green Performance Prediction*

In addition to the types of performance considered traditionally in building design, such as spatial arrangement, esthetic appeal, cost, etc., green design requires consideration of a variety of criteria related to the building's effects on the environment. Energy is one of the most important considerations due to the significant environmental impacts of energy production. While energy requirements have been initially considered with respect to the building's operation, significant efforts are under way to better understand the energy and environmental performance of the manufacturing of building components and systems and the construction and demolition of buildings.

Performance prediction with respect to energy and environmental impact may require massive computations, depending on the building modeled and the accuracy desired. Significant efforts over the last twenty-five years have resulted in sophisticated computer-based simulations of the operation of buildings for the computation of energy requirements for lighting, heating, cooling, ventilation, etc. Similar efforts during the last decade are resulting in tools that address the energy requirements for the manufacturing of building components and systems and the construction and demolition of the building itself. Moreover, a variety of green performance assessment tools are becoming available, most of which are in the form of rating systems based on sets of predefined criteria.

### *Available Tools*

The oil crises of the 1970s resulted in several efforts to understand building operating energy issues and develop energy efficient strategies and technologies. These efforts have resulted in several computer-based simulation tools, such as the DOE-2 building energy simulation tool (Birdsall at al., 1990; Winkelmann at al., 1993), the COMIS ventilation and indoor air quality tool (Feustel, 1992), the Radiance lighting simulation and rendering tool (Ward and Shakespear, 1998), etc. Most of these tools were originally developed for research purposes and have been used extensively for the design and development of new strategies and technologies, which significantly improve building energy and environmental performance.

Relative to the operating energy requirements of buildings, the importance of the embodied energy of materials and the environmental impact of building construction, operation and demolition has been only recently realized. The available tools lack the sophistication of operating energy tools. However, they are becoming increasingly capable and accurate, as better understanding of the related phenomena lead to the design and development of increasingly sophisticated models for performance prediction, such as the ATHENA building materials life-cycle analysis tool (Trusty and Meil, 1997).

### *Shortcomings of Available Tools*

Most sophisticated simulation tools that offer potential for high accuracy are very hard to use. Reliable and effective use requires knowledge and understanding of the underlying models and incorporated assumptions. They usually require the preparation of input files, which require description of the building and its context using specific syntax and keywords (Figure 2). The learning period for the preparation of the input can be several months long and even then, the preparation of input files may take days to weeks, depending on the complexity of the design. The same is true with the output of most tools, which is usually in the form of alphanumeric tables that are hard to understand and interpret (Figure 3). Some tools, like Radiance, provide output in excellent formats for interpretation of results (Figure 4).

```
INPUT LOADS   ..
TITLE LINE-1 * MEDICAL OFFICE BUILDING, CHICAGO*
      LINE-2 * WATER LOOP HEAT PUMP WITH STORAGE *
      LINE-3 * SAMP3.INP  RUN 1  *  ..

               ABORT                ERRORS   ..
               DIAGNOSTIC           WARNINGS    ..
               RUN-PERIOD           JAN 1 1988  THRU  DEC 31 1988  ..
               BUILDING-LOCATION    LATITUDE=42  LONGITUDE=88
                                    TIME-ZONE=6  ALTITUDE=610 ..

               LOADS-REPORT         SUMMARY=(LS-B,LS-C,LS-D) ..

ROOF-O        =LAYERS               MAT=(BR01,IN76,CC03,AL33,AC03)  I-F-R=.76 ..
ROOF-A        =LAYERS               MAT=(BR01,IN76,CC04)  I-F-R .76  ..
OFF-ROF       =CONSTRUCTION         LAYERS ROOF-O  ..
ATR-ROF       =CONSTRUCTION         LAYERS ROOF-A  ..
WALL-1        =LAYERS               MAT=(CC33,IN35,AL21,GP04,GP04)  ..
WL1           =CONSTRUCTION         LAYERS=WALL-1  ..
BW1           =CONSTRUCTION         U=.05 ..
BW2           =CONSTRUCTION         U=.0001   ..
WL2           =CONSTRUCTION         U=1.05   $ ATRIUM GLASS PARTITIONS $  ..
WL3           =CONSTRUCTION         U=.28    $ INTERIOR PARTITIONS $  ..
```

**(a)**

```
# Rad control file for atct5
AMBFILE= atct5.amb
DETAIL= High
EXPOSURE= -1
INDIRECT= 1
OCTREE= atct5.oct
OPTFILE= atct5.opt
PENUMBRAS= False
PICTURE= pic/atct5
QUALITY= Med
REPORT= 60
RESOLUTION= 1024
UP= Z
VARIABILITY= High
ZONE= I -128.749 246.956 -189.286 185.669 -5.06 204
materials= atct.mat alias.mat
render= -w -st .005 -ae c111 -ae ground_mat -ae water
view= cyl -vtc -vp 152 -125 60 -vd -0.703298 0.706112 -0.0823329 -vh 180 -vv 60
view= cona -vp 25 -20 55 -vd -0.1134 -0.985616 -0.125309 -vh 35.2647 -vv 24.672
view= runw -vp 40 60 60 -vd -0.192224 0.981351 0 -vh 62.5 -vv 44.7 -vl -0.2
```

**(b)**

**Figure 2**. Sample screens from input files to DOE-2 (a) and Radiance (b).

```
SPACE TEMPERATURE USED FOR THE LOADS CALCULATION IS   74 F /  23 C

                   MULTIPLIER        1.0          FLOOR MULTIPLIER        1.0
                   FLOOR  AREA      3230  SQFT       300   M2
                   VOLUME          29070  CUFT       823   M3

                                          COOLING  LOAD                          HEATING  LOAD
                                     ==========================           ==========================
    TIME                                   AUG 19  4PM                             JAN  1  9AM

    DRY-BULB TEMP                       90 F             32 C                  -2 F          -19 C
    WET-BULB TEMP                       71 F             22 C                  -2 F          -19 C
    TOT HORIZONTAL SOLAR RAD           218 BTU/H.SQFT   687 W/M2               38 BTU/H.SQFT  118 W/M2
    WINDSPEED AT SPACE                 5.2 KTS          2.7 M/S               5.9 KTS         3.0 M/S
    CLOUD AMOUNT 0(CLEAR)-10             0                                      0

                              SENSIBLE            LATENT                           SENSIBLE
                         (KBTU/H)    ( KW )  (KBTU/H)  ( KW )                 (KBTU/H)  ( KW )
                         --------    ------  --------  ------                 --------  --------

     WALL CONDUCTION        2.425     0.711     0.000   0.000                   -7.498    -2.197
     ROOF CONDUCTION        0.000     0.000     0.000   0.000                    0.000     0.000
     WINDOW GLASS+FRM COND 15.484     4.537     0.000   0.000                  -26.822    -7.859
```

**Figure 3**. Sample screen from output file from DOE-2.

(a)

(b)

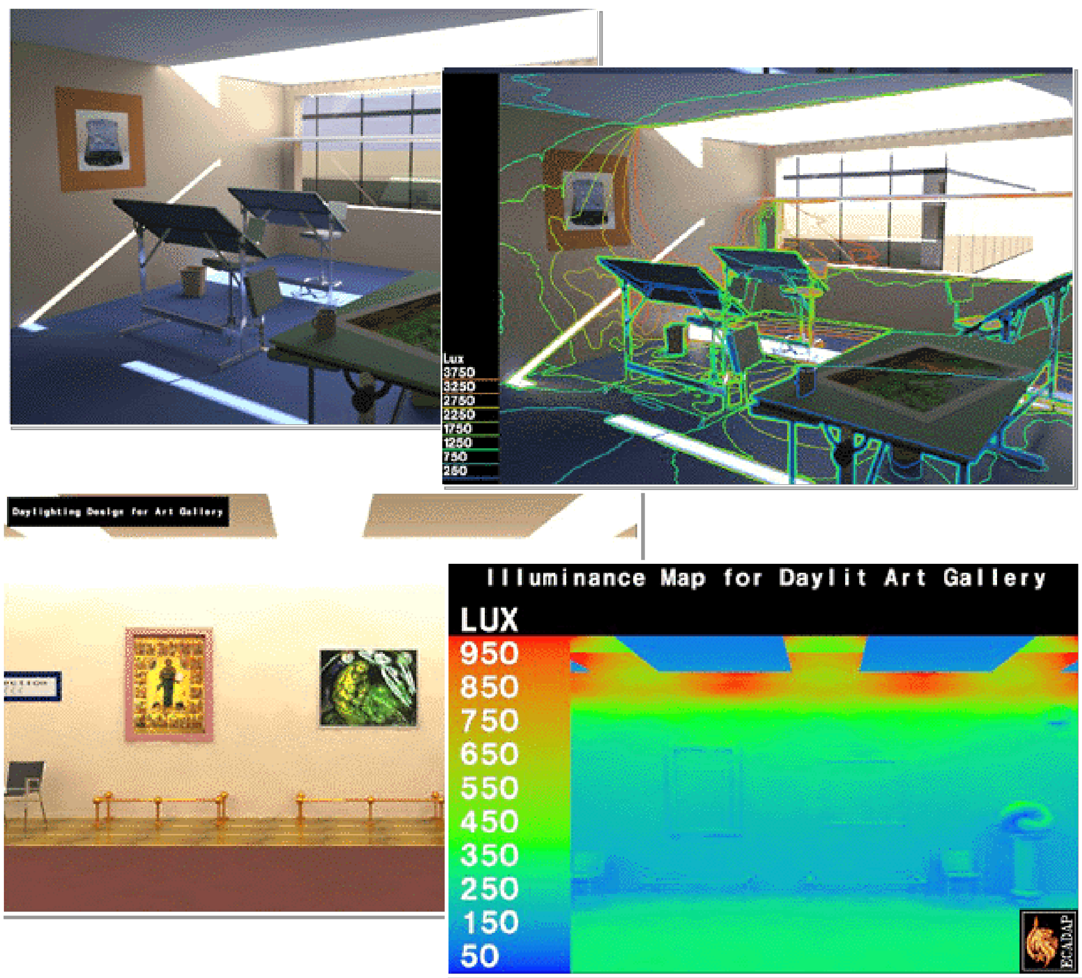


**Figure 4**. Sample output of Radiance, showing (a) standard rendering with and without superimposed illuminance contours and (b) standard rendering and false color display of illuminance values.

Since different simulation tools use different models, the use of multiple tools requires repetitive description of the building and its context in different formats. A thermal simulation tool, for example, requires description of the building in terms of "thermal barriers" with thermal properties, such as U-value, solar heat gain coefficient, etc. A lighting simulation tool requires description in terms of "polygons" with optical properties, such as transmittance, reflectance, etc. These repetitive descriptions are unattractive and time-consuming, which makes them costly.

Most of the sophisticated tools require detailed information about the building and its context, such as material properties, operating schedules, thermostat settings, etc., which are usually not available during the initial, schematic phases of building design. As a result, these tools are used after many important decisions about the massing and orientation of the building have already been made. Such decisions usually have a strong effect on the energy and environmental performance of buildings and it may be very expensive to change them, having to reconsider all of the follow-up decisions.

### *Emerging Tools*

Combined with the increased interest in the effects of buildings on the environment, the phenomenal decrease in the cost of computing power has resulted in PC versions of several sophisticated tools, like DOE-2 and Radiance, which were originally developed for mini and super computers. The potential for wider distributions, offering business opportunities, has resulted in several commercial versions with graphical front and back ends, which facilitate the preparation of the input and the review and interpretation of the output, such as several DOE-2-based PC tools (Simulation Research Group, 1999) and Desktop Radiance, which facilitates the use of Radiance through links to commercial CAD (Papamichael et al., 1998). Most of these tools, however, support only a fraction of the total capabilities of the simulation engines that they control.

New simulation tools with graphical user interfaces are also being developed such as Energy-10 (Balcomb, 1997), as well as "tool-kit" environments that facilitate the integrated use of multiple tools, like the Building Design Advisor (BDA), which supports the automated preparation of input to and handling of output from multiple simulation tools, by mapping a single building model to the individual models required by the different simulation tools (Papamichael, 1999). These tools are just emerging from research and are currently reviewed towards better understanding of industry needs and desires for the development of commercial versions. In the meantime, new simulation tools are being developed to improve modeling capabilities and prediction accuracy, like Energy Plus (Crawley et al., 1999). Efforts are also underway for the standardization of building modeling in terms of interrelated objects, so that software tools become interoperable (Bazjanac and Crawley, 1997).

New CAD tools are also emerging, using building representations, as opposed to representations of drawings, thus offering potential for integration with simulation tools that will not only facilitate their use, but spread it as well, since CAD systems are already in wide use by building designers. Lately, several web-based simulation services have also emerged, which allow designers to submit their designs and receive simulation reports through the Internet.

## Performance Assessment

Performance *assessment* is the evaluation of predicted performance, which requires knowledge of what is desired and what is possible. Assessment involves performance comparisons among alternative design options and between design options and actual buildings or performance standards. The former requires performance prediction for all alternative design options, while the latter requires availability or formulation of performance standards and/or availability of data for the performance of existing buildings.

### *Green Performance Assessment*

In addition to green performance prediction, green performance assessment requires the formulation of green performance criteria and standards, along with green performance data for existing buildings, which are critical in understanding what may be possible.

### *Available Tools*

Several of the emerging tools include capabilities of comparing performance among design alternatives, like the BDA. Others are designed to check compliance with energy and environmental performance codes and standards. Codes and standards, however, may not be appropriate for good design, since their purpose is merely to prevent bad designs. Several green performance assessment tools are available in the form of rating systems, based on sets of predefined criteria, like BREEAM (Building Research Establishment, 1991) and BEPAC (Cole et al., 1993).

Green performance data for available buildings are limited to a few databases, like CBECS, and a limited number of case studies on the performance of actual buildings. Fortunately, most case studies focus on good examples of green buildings, which not only provide higher standards for performance assessment, but offer information about the integration of green strategies and technologies for performance improvement as well.

Performance-based contracting and green design incentive programs have the potential to increase the available data as well as our understanding of the performance of strategies and technologies under a variety of contexts. However, significant work is required to compile and organize data for quick and easy access and make them available during the building design process in ways that facilitate performance assessment.

## Performance Prediction Accuracy

The accuracy of performance prediction depends on the model used and the accuracy of the input, which in turn depends on the person using the model. Accurate input requires a realistic understanding of how buildings are actually managed and used by occupants.

### *The Role of the Software Tool*

Different tools use different models, with different modeling capabilities and levels of prediction accuracy. Increased sophistication in the simulation model usually results in increased modeling capabilities and accuracy. Sophisticated models, however, usually require more detailed input and more computing power. Considering the prediction of daylighting performance, for example, most simplified daylight simulation tools, like LumenMicro (Baty 1996), are fast and relatively easy to use. However, they can only model simple, orthogonal, empty spaces, with simple, rectangular windows. Complications in spatial geometry require use of sophisticated simulation tools, like Radiance (Ward and Shakespear, 1998), which are much harder to use and require significant computing power. Unfortunately, for the case of daylighting prediction, most advanced daylighting technologies, such as light-shelves, are too complex for proper modeling using simplified tools.

A similar situation exists with energy analysis tools, some of which, like DOE-2 (Birdsall et al., 1990; Winkelmann et al., 1993), focus on modeling sophistication for high accuracy, while others, like ASEAM (ACEC, 1991), focus on reducing computation time requirements for quick, "order of magnitude" prediction and assessment.

The accuracy of the input to simulation model significantly affects the accuracy of the predicted performance. Considering daylighting, for example, even the most sophisticated simulation programs, like Radiance, may produce inaccurate results because of inaccurate data on surface properties and sky luminance distribution. The available standardized sky models, like the CIE sky luminance distributions, may not represent the sky conditions at the specific site of the building under design.

### *The Role of the Software User*

At the current form of most tools, the user plays a very important role on the accuracy of the predicted performance. Simulation tools use conceptual models of the building and its operation, which must be well understood for the preparation of their input. In many cases, buildings are modeled incorrectly, resulting in inaccurate performance prediction, which may not even be noticed, increasing the chances of failing to achieve desired performance.

Expert users know the modeling idiosyncrasies of the available tools and have more chances of preparing appropriate input. In many cases, they use "tricks" to get the most out of available tools. Experienced Radiance users, for example, know that Radiance computes the propagation of light considering random rays from the eye of the observer and following their reflection by and transmission through surfaces, until they hit a light source. When modeling long and narrow skylights, they usually consider an intermediate, imaginary surface at the bottom of the skylight, compute its luminance by first simulating the light propagation inside the skylight, and then use the imaginary surface as a light source to compute the light propagation in the space.

Experienced energy and environmental consultants use a variety of tools, depending on the performance issue addressed and the prediction accuracy desired. In many cases, they use the output of one tool as input to another. A specialist, for example, may use tools like Optics, Therm and Window (Arasteh et al., 1999) to determine the solar optical and thermal properties of a custom window for which data are not available.

Even if the modeling idiosyncrasies are properly handled, simulation can only provide answers about the performance of a specific design. The generation of ideas towards performance improvement still requires specialized knowledge, which is more likely to be found in experts rather than novices. In addition to increased reliability on simulation results, experienced specialists are more likely to assist with suggestions for design changes with potential to improve performance.

In many cases, the involvement of an experienced user may end up costing less than the involvement of a novice, because of reduced times for the preparation of input data and interpretation of results. Considering the increased confidence on performance prediction and assessment, as well as the potential for design advice that experienced users have, they offer significantly increased value compared to novices.

## Performance Prediction/Assessment Costs

The cost of performance prediction depends on the tools used and the way they are used. Sophisticated tools that offer high accuracy require increased computing power and user experience. The cost of computing equipment is becoming less of an issue, mainly because computers are already available in most building design offices. The cost of software can vary from a few hundred U.S. dollars for simplified tools, to several thousand U.S. dollars for sophisticated tools. In many cases, sophisticated tools may be deceivingly inexpensive, or even offered free of charge, mainly because they are too complex for wide use that would present commercial value. In general, however, the cost of hardware and software is small compared to the cost of the user, which can vary from approximately $15/hour for knowledgeable students up to $70/hour for professionals and maybe $150/hour for experts. The total simulation cost for a project can vary from a few to several thousand dollars, depending on the complexity of the building and the design iterations considered (Figure 5).

The main initial task of the simulation specialist is to develop a model of the building under design. Depending on the design phase that the specialist is brought in, this task may take a significant time. If most of the design is complete, as is usually the case, it may take from a few days to a few weeks, depending on the size and the complexity of the building, as well as the level of the accuracy desired. The cost of additional simulations, after the initial model is complete, depends on the level of the design changes. The cost also varies with respect to the size, complexity and repetitiveness of the building design, ranging from $.03/sqft to $.20/sqft. The cost for a 10,000-sqft building, for example, can vary from $3,000 to $20,000. The cost of the recently available Web-based simulation services is in the range of a few to several hundred U.S. dollars per simulation run.

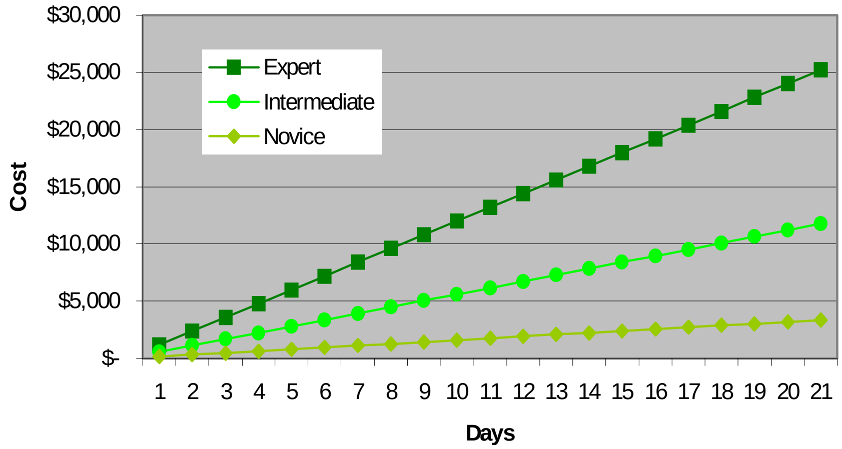


**Figure 5**. Approximate cost of simulation specialists for experts, intermediate and novices.

The cost of using energy or environmental specialists, however, goes beyond their fees. Once involved, they may significantly affect the timing of the overall design process, certainly increasing time requirements for performance prediction. Moreover, they take up time from other design participants, for the clarification of building design details, the communication of the results and the generation of new ideas towards performance improvement. New ideas, must, of course, be evaluated not only with respect to energy and environmental impact, but with respect to all other criteria as well, which may have significant effects on the overall design costs.

### Performance Prediction/Assessment Benefits

The benefits of green performance prediction and assessment may be very significant, depending on the scope of the analysis. The cost of accurate simulations may be recovered in various ways, like downsizing HVAC equipment and reducing operational costs. However, building owners, not designers, realize such savings. In many cases, designers may be penalized for producing more energy efficient designs. If the basis for HVAC engineers fee, for example, is the size of the HVAC equipment, it is not to their economic advantage to reduce energy requirements, because they will also reduce the equipment size and thus their fee.

Programs like CANMET's C-2000 (Larsson, 1993, 1995) take special care to account for such problems, by specifying fees of up front. Moreover, they encourage collaboration of all interested parties from the early, schematic phases of building design and provide facilitators, which are most valuable for enhancing communications and guiding the overall process.

Design/build approaches address performance issues through rewards and penalties, based on measured performance data from the operation of the actual building, after it is built. California utilities recently announced new programs that are even more attractive, like "Savings by Design," which offers incentives of up to $250,000 for building owners and $100,000 for building designers depending on the energy performance improvement relative to the California Energy Code requirements. Like the C-2000 program, they also encourage a "whole building design approach" and encourage early collaboration of owners, architects and engineers.

## Conclusions

Green performance prediction and assessment requires use of complex tools, usually in the form of computer-based simulations, which can vary significantly with respect to their modeling capabilities and prediction accuracy. Performance assessment requires comparison among design options, as well as between design options and performance standards or existing buildings. Several tools are available, most of which are hard and time-consuming to use.

The accuracy of performance prediction depends highly on the tools used and the way they are used. Most sophisticated tools, with advanced modeling capabilities, require experienced users to assure proper preparation of input and interpretation of output. Although more expensive, experienced energy and environmental consultants usually offer increased value compared to novices, not only because of increased confidence in performance prediction and assessment, but potential for design advice towards performance improvement as well.

Computers will eventually make energy and environmental impact simulations easier and faster. Links between simulation tools and the new, improved CAD software that differentiate building components and systems will greatly facilitate the advancement of integrated tools that support accurate performance prediction and assessment from the initial, schematic phases of building design. Such tools, combined with the new telecommunication capabilities of the Internet, have the potential to significantly reduce the costs of collaboration throughout the building design process and greatly improve performance prediction assessment for informed decisions towards better and greener buildings.

## Acknowledgements

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